



**AFRL-OSR-VA-TR-2013-0137**

**Wave and Mode Interaction in Overmoded High-Power Amplifiers of  
Short-Wavelength Radiation (from W-band up to THz)**

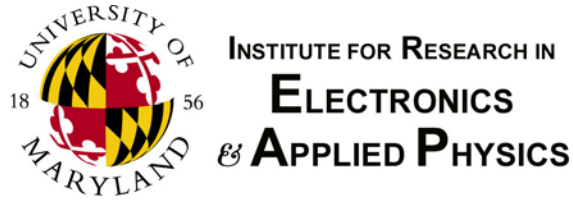
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University of Maryland**

**April 2013  
Final Report**

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14. ABSTRACT This work was done in the following directions: 1. Excitation of parasitic waves near cutoff in forward-wave amplifiers; 2. Periodic dielectric slow-wave structures; 3. Role of metallic dust on operation of high-power sources of electromagnetic radiation. The problem of excitation of dangerous parasitic modes in high-power amplifiers operating in high-order waves was studied, first, assuming strong focusing fields, in which electrons perform 1D motion. Then, the approach was generalized to the case of weak guiding fields, in which electrons exhibit 3D motion. The effect of guiding fields and other parameters on the conditions of parasitic excitation was analyzed and illustrated by design examples. Periodic dielectric slow-wave structures may exhibit an interesting class of new metamaterials attractive for high-power, millimeter-wave amplifiers. The theory of such structures has been developed and illustrated by some examples. Heating and melting of small micro-particles (metallic dust) in strong microwave fields may initiate the breakdown events in high-power microwave (HPM) sources. These processes have been studied in HPM sources operating in rep-rate regimes.					
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**Final Report**  
**on the project “Wave and Mode Interaction in Overmoded High-Power**  
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**(AFOSR FAS9550-09-1-0670)**  
**to the project manager,**  
**Dr. John Luginsland**

**Principal Investigator,**  
**Gregory S. Nusinovich**

**June 2012**

This report summarizes results of the work performed at the Institute for Research in Electronics and Applied Physics of the University of Maryland (College Park, MD) in the framework of the AFOSR Project “Wave and Mode Interaction in Overmoded High-Power Amplifiers of Short Wavelength Radiation (from W-band up to THz)”. This work was started in September 2009 and was going on in the following directions:

1. Excitation of parasitic waves near cutoff in forward-wave amplifiers;
2. Periodic dielectric slow-wave structures;
3. Role of metallic dust on operation of high-power sources of electromagnetic radiation.

Prior to describing our accomplishments in the studies along these lines, let us explain the motivation for our choice.

#### 1. Excitation of parasitic waves near cutoff in forward-wave amplifiers.

To achieve high-power level of radiation at very short wavelengths it is necessary to design such amplifiers for operation in high-order modes. As known, for stable operation of any amplifier the excitation of parasitic oscillations is, possibly, the most important obstacle. In the case of operation in higher order modes, a number of parasitic modes which prevent stable amplification increases, thus making realization of high gain regimes practically impossible. In this regard, especially dangerous are parasitic modes which can be excited near cutoff, as shown in Figure 1. As shown in Fig. 1, in addition to intersecting the dispersion curve of the desired signal wave, the electron beam line corresponding to the Cherenkov synchronism between electrons and the phase velocity of the wave can also intersect the dispersion curve of the parasitic mode near the  $\pi$ -point.

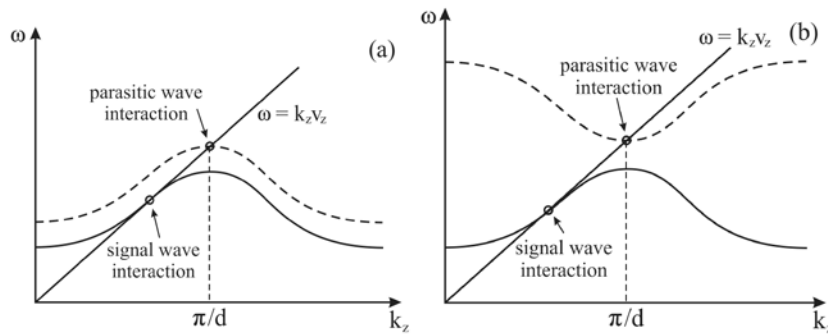


Figure 1. Excitation of parasitic modes near cutoff in slow-wave structures with normal (a) and anomalous (b) dispersion characteristics.

As known, in the vicinity of  $\pi$ -point, the group velocity is small and, therefore, the beam coupling to such waves is very strong. So, just such cutoff modes can be easily excited by a beam. This fact had motivated our interest to the study.

## 2. Periodic dielectric slow-wave structures

It is known that fabrication of metallic slow-wave structures for short wavelength operation is becoming more and more difficult as the wavelength shortens. There are also some experiments demonstrating that the breakdown threshold in dielectrics can be higher than in metals, so that dielectric structures can withstand higher power levels of operation. This is why there is a certain interest in using the dielectrics instead of metallic slow-wave structures. So far, this interest was primarily restricted by the analysis of simplest smooth-wall dielectric structures which can be easily fabricated. In addition to this class of structures, dielectric structures which contain some periodic elements and therefore which can be considered as a class of *metamaterials* may be of interest. Those can be either periodic dielectrics or smooth-wall dielectrics with a metallic periodic circuit, e.g., a helix, on its inner surface. Such structures, first, can be used for developing backward-wave devices, in contrast to smooth-wall dielectrics in which there is no backward waves. Second, in the case of periodic dielectric slow-wave structures one can envision the forward-wave operation with an electron beam synchronous with the first space harmonic. Such operation can be realized at much lower beam voltages which is advantageous for many applications. These arguments had stimulated our interest to studying such slow-wave structures.

## 3.Role of metallic dust

In the circuits of high-power microwave (HPM) sources small quantities of metallic dust may exist. These metallic particles of a micron size being located in the region of high RF fields can absorb enough energy for significant heating and even melting. The melted clumps can then impinge on structure surface and create non-uniformities leading to the RF field enhancement and subsequent breakdown events. Therefore the analysis of conditions leading to melting of such small metallic particles in strong RF fields can help to formulate some limits for reliable operation of HPM sources. We have started to study this problem for the case of single pulse operation. In the framework of this three-year

term, we generalized our analysis for the case of rep-rate operation and included both the RF magnetic and electric fields into consideration.

Our results are briefly described below.

### **Excitation of parasitic waves near cutoff in forward-wave amplifiers.**

The study of excitation of parasitic waves near cutoff in forward-wave amplifiers consists of two stages. First, we analyze steady-state operation of a forward-wave amplifier itself. This analysis was performed in the simplest general form, i.e. we used normalized variables of the same sort as those used by J. Pierce in his linear theory of traveling-wave tubes (TWTs) and later, used by L. Weinstein in the nonlinear theory of TWTs. The second stage was devoted to the analysis of the conditions of self-excitation of parasitic waves near cutoff in the presence of a forward signal wave. It was shown that such waves can be excited when the gain function of the parasitic wave exceeds a certain critical value defined by the ratio of the coupling impedances (Pierce-like gain parameters) for both waves. It should be emphasized that this gain function of the parasitic mode takes into account the effect of electron bunching in the field of large-amplitude signal wave.

First, this analysis has been performed for the case of 1D electron motion in strong focusing magnetic fields. Results of this study were reported in Ref. 1 and described in Ref. 2. Then, we generalized our treatment for the case of 3D motion which is the case of operation in weak focusing magnetic fields, the case advantageous for many applications (including airborne and satellite ones). Results of the latter study were presented at the APS-DPP 2012 Meeting [3] and published in Ref. 4. Figures 2 and 3 illustrate some of our results.

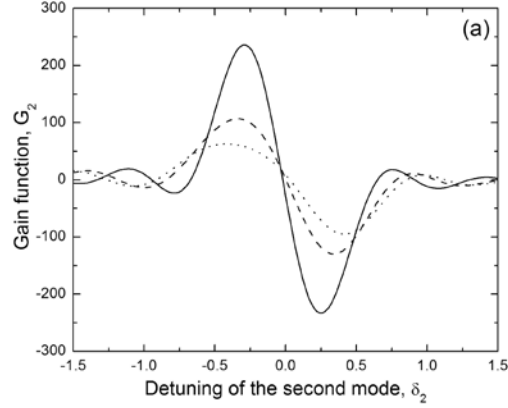


Figure 2. Gain function of the parasitic wave as the function of the second mode detuning of resonance between electrons and the wave for the case of exact synchronism between electrons and the forward wave. Solid, dashed and dotted lines correspond to the initial normalized amplitude of the signal wave equal to 0.001, 0.01 and 0.1, respectively.

Results shown in Figure 2 illustrate the effect of suppression of the parasitic wave by a signal wave: as the input amplitude of the signal wave increases, the peak of the gain function of the parasitic wave gets smaller. At the same time, however, the region of detunings  $\delta_2$  where the gain function is positive and, hence, the excitation is possible widens at negative detunings less than -0.6. This illustrates the effect of nonlinear excitation (also known as cross-excitation) caused by the fact that at these detunings the signal wave provides electron bunching favorable for excitation of the parasitic mode.

Results shown in Figure 3 illustrate the effect of the guiding magnetic field (parameter  $M$  is proportional to the magnetic field) on the excitation of parasitic waves near cutoff. As one can see, the increase in guiding magnetic field has small effect on the device gain, but reduces the device bandwidth (shown as BW in the figure).

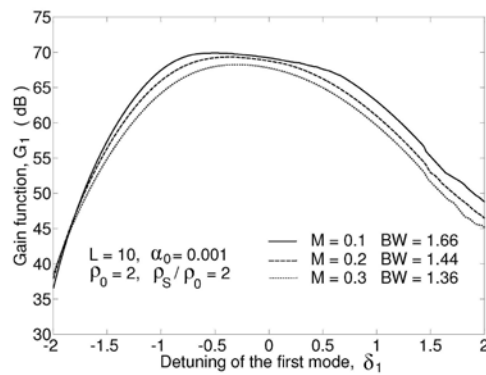


Figure 3. Gain of the signal wave as the function of the detuning of Cherenkov synchronism for different values of the magnetic field parameter  $M$ . Solid, dashed and dotted lines correspond to  $M = 0.1, 0.2, 0.3$ , respectively. The detuning is normalized to the Pierce gain parameter.

## Dielectric slow-wave structures

Our study of dielectric slow-wave structures has also consisted of two parts. In the course of the first one, we analyzed some properties of periodic dielectric slow-wave structure. The second part is the study of a dielectric structure with a periodical metallic circuit on its inner surface.

Periodic dielectrics can be treated in the same fashion as periodic metallic slow-wave circuits. A schematic of a circuit is shown in Fig. 4. To derive the dispersion equation for the waves in such a circuit one, in accordance with the Floquet's theorem, should represent the fields in each region of a one period as a sum of space harmonics and use corresponding boundary conditions to match these representations.

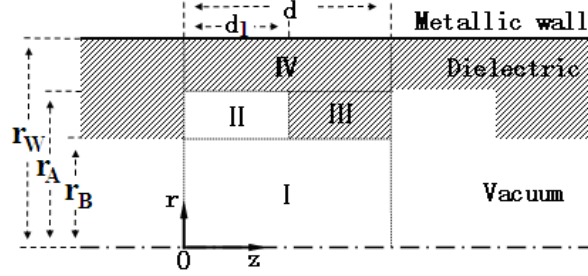


Figure 4. Schematic of a periodic dielectric circuit

Such analysis was carried out by two methods known as the integrating approach and the point sampling approach. Comparison of results showed that they agree very well (see left Figure 5), while the point sampling approach requires much shorter computational time. Results of both approaches also agree very well with HFSS simulations as shown in Figure 5 on the right.

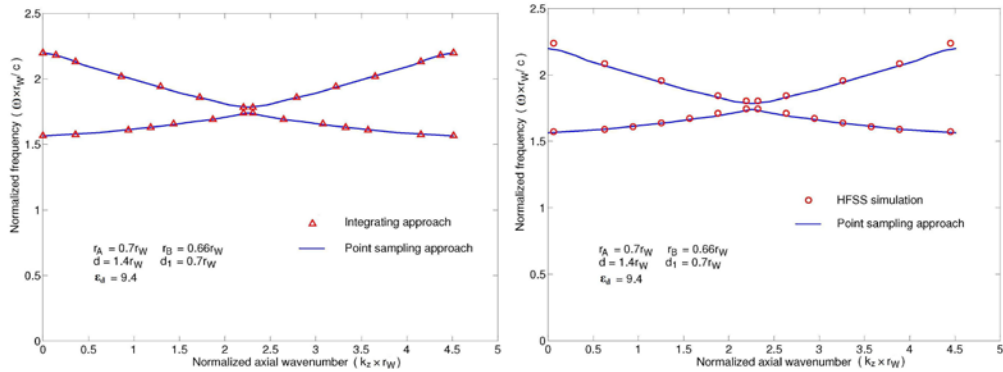


Figure 5. Dispersion characteristics calculated by different methods.



For illustration, in Figure 6 several examples of W-band alumina structures driven by a 30 keV electron beam are shown. Here the left figure corresponds to the TWT in which an electron beam interacts with the zero space harmonic of a wave. The central figure corresponds to the backward wave interaction of an electron beam with the wave having a negative group velocity. The right figure corresponds to the beam interaction with the first space harmonic of the forward wave.

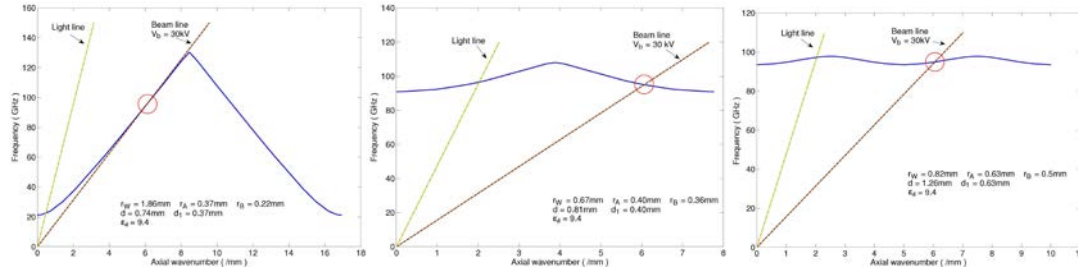


Figure 6. Examples of dispersion characteristics of W-band structures with a periodic dielectric. A 30 kV electron beam interacts with (a) the zero space harmonic of the forward wave, (b) the first space harmonic of the backward wave, (c) the first space harmonic of the forward wave.

Results of these studies can be used for designing high-power short-wavelength vacuum electron amplifiers and oscillators. These results were reported in Ref. 5 and described in Ref. 6.

### Planar Sheath Structures

We have undertaken a study of planar, slow wave interaction structures based on a sheath model. The general geometry we consider is illustrated in Fig. 7. The structure consists of two dielectric layers with wire sheaths deposited on them, sandwiched between two conducting backing surfaces. The wire sheaths have opposite pitches on the upper and lower surfaces. The structure can be thought of as a planar version of the sheath helix model used to describe tape helix traveling wave tubes. We are initially considering the wire sheath model, but a natural generalization is to replace the sheath clad dielectric with a layered meta-material that has an anisotropic dielectric constant with principle axes that reverse signs from top to bottom.

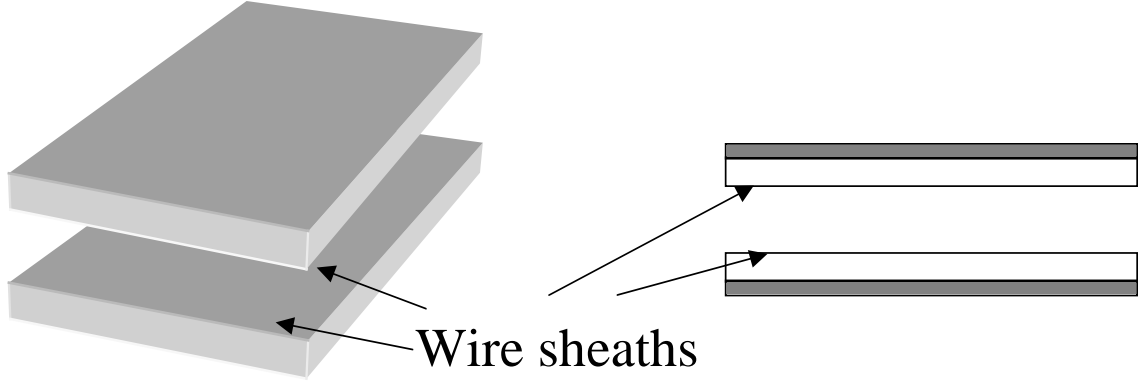


Figure 7. Planar structure with wire sheaths deposited on dielectric layers.

The dispersion curve for a sample structure is illustrated in Fig. 8. The structure supports modes that have highly linear dispersion characteristics indicating a potential for broad bandwidth. In the limit of transverse wavenumber  $k_y = 0$ , the structure supports modes that are either odd or even with respect to the horizontal symmetry plane. The axial field of the lower frequency mode is even and will strongly interact with a planar electron beam. Because of the opposite direction of the wire pitch on the two surfaces the symmetry is broken for modes with  $k_y \neq 0$ .

The advantage of such a structure is as follows. The slow waves are achieved due to the anisotropic wire sheath, not due to the high dielectric constant of the layers. Thus, the field Poynting flux is mainly in the vacuum region, not in the dielectric region, and the interaction impedance can be high. Second, the slow waves are not created by the periodicity of the wire mesh, rather by its anisotropy. Thus, by making the period of the mesh very small, possible backward waves, and pi-points where group velocity vanishes, can be moved to much higher frequency than the operation point. This is in contrast to coupled cavity structures where the slow waves are linked to the period of the structure, and competing higher order modes and associated stop bands are an issue. Third, the structure lends itself to interaction with a sheet beam. Fourth, the structure is totally planar which should aid in fabrication. Finally, although there is a potential for transverse mode competition associated with modes with different values of  $k_y$ , these modes will propagate laterally out of the interaction region and can thus be suppressed by absorbing materials that do not influence the fields of the mode with  $k_y = 0$ .

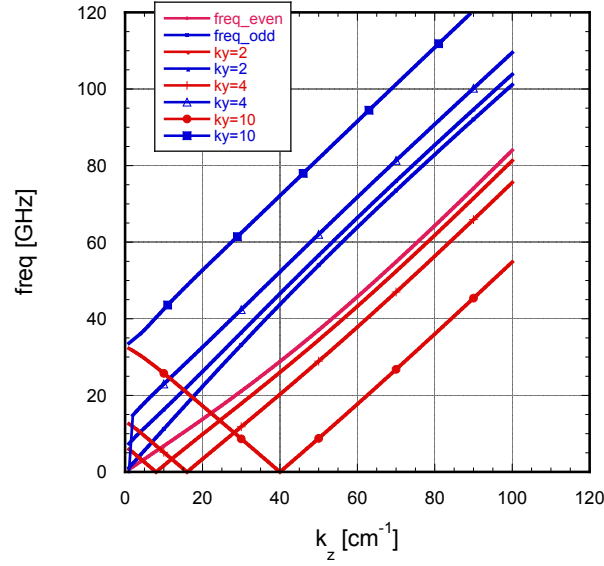


Figure 8. Dispersion curves for a structure with a .1 mm gap and a wire pitch of 0.25 for various values of transverse wavenumber.

Our study of this structure has just begun; we plan to consider modeling the interaction with an electron beam, schemes for damping modes with high transverse wavenumber, and consideration of alternate structures, e.g. layer dielectrics for the anisotropic slow wave geometry.

### **Role of metallic dust**

For a number of reasons, in any microwave source there can be a certain amount of metallic dust, i.e. metallic microparticles with micron-scale dimensions. Such microparticles have dimensions much smaller than a wavelength, but these dimensions can be on the order of the skin depth. In such a case, such microparticles can efficiently absorb microwave energy and, hence, in long enough pulses of high power be heated and melted. Then, such melted clumps can impinge the surface of microwave circuits. This may cause appearance of footprints leading to the field enhancement and, therefore, stimulating RF breakdowns in succeeding pulses which result in the erosion of the circuit surface.

We have started analyzing these processes, first, in application to high-gradient accelerating structures where we analyzed the role of the RF magnetic field in single

pulses [ G. S. Nusinovich, D. Kashyn and T. M. Antonsen, Jr., Phys. Rev. Special Topics – Accelerators and Beams, **12**, 101001 (2009)]. Then, in the framework of the present grant, we have extended our treatment for the case of rep-rate operation of HPM devices and accelerating structures; corresponding results were reported in [7] and described in Ref. 8. Figure 9 illustrates the gradual increase of the temperature of such a copper microparticle (a sphere of the radius equal to 4 skin depth values at the room temperature) due to the RF (11.424 GHz frequency) magnetic field in a series of pulses.

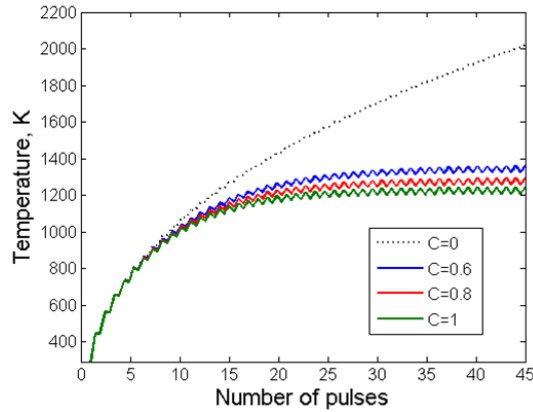


Figure 9. Temperature rise as the function of a number of 500 nsec pulses with a 100 Hz repetition frequency. The amplitude of the RF magnetic field is 0.5 MA/m. Different values of the parameter  $C$  correspond to the uncertainty in the efficiency of thermal blackbody radiation between pulses:  $C=1$  corresponds to the condition of blackbody radiation in accordance with the Stefan-Boltzmann law; the values  $C<1$  characterize the fact that our “gray” microparticle emits less radiation than a black body. The factor  $C$  is equivalent to shortening the time interval between pulses, i.e. increasing the duty cycle of operation. The dashed line shows the temperature rise in a single long RF pulse in the absence of thermal emission.

After studying the effect of RF magnetic fields, which is the dominant effect in the case of micro-particles of a smooth shape (like spheres), we focused on a possible effect of RF electric fields for heating of micro-particles with sharp boundaries. The shape of a micro-particle was modeled by an ellipsoid (shown in Fig. 10a) whose ratio  $R$  of semi-axes describes the configuration of possible particles and corresponding enhancement of the RF electric field on its ends:  $R=1$  corresponds to a sphere where the field enhancement factor is equal to 3, while at  $R \gg 1$  the field enhancement factor can exceed 100. Corresponding dependence of the field amplification factor on the height-to-radius ratio of a microparticle is shown in Figure 10b which shows that in RF electric fields on the order of 1 MV/cm achievable in HPM devices the height-to-radius ratio should be about 100 in order for making the field emission (in the fields exceeding 5 GV/m) from the tips of this micro-particle possible. Thus, the field emission leading to

substantial Joule heating of micro-particles is possible only in the case of needle-like configurations.

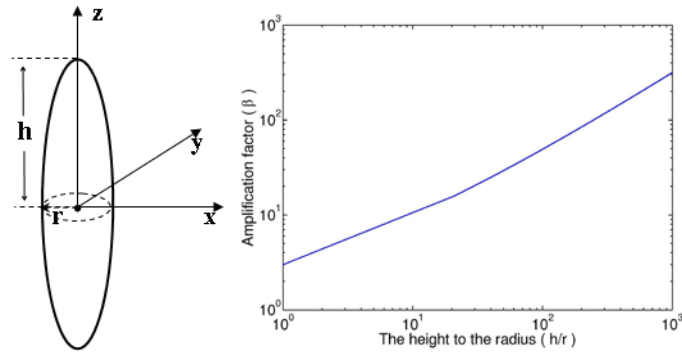


Figure 10. Left (a): Geometry of an ellipsoid under study; right (b): Field amplification factor as the function of the height-to-radius ratio.

Resulting contribution of both RF magnetic and RF electric fields to the heating of micro-particles is illustrated by Fig. 11 where the temperature rise in a copper micro-particle due to the RF electric field is shown for several values of the field; also the black curve shows the temperature rise due to the RF magnetic field. As one can see, at pulse durations up to 20 microseconds, the role of the RF electric field in heating is comparable to the role of the RF magnetic field (0.5 MA/m) when the RF electric field on the tips of a particle is in the range of 7.25-7.5 MV/m values. This study is described in Ref. 9.

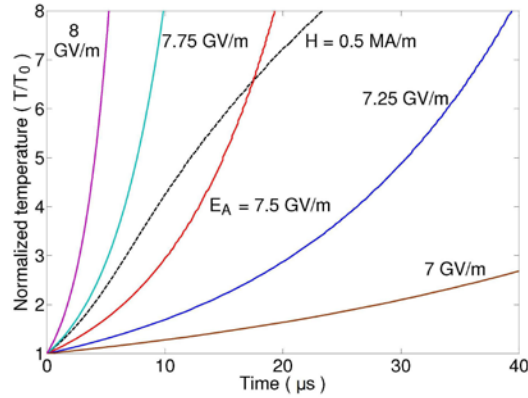


Figure 11. Temperature (normalized to the initial room temperature) as the function of microwave pulse duration for several values of the RF electric field on the tips of a micro-ellipsoid; black curve shows the temperature rise due to the RF magnetic field.

### **Executive Summary**

In the course of the present grant, our group consisting of Dr. G. S. Nusinovich (PI), Prof. T. M. Antonsen, Jr. (Co-PI), assistant research scientist O. V. Sinitsyn (Co-PI), visiting scientist Y. Han and graduate students B. Nguyen and D. G. Kashyn has performed a number of studies important for operation of high-power and high-frequency sources of coherent electromagnetic radiation. Our accomplishments can be briefly summarized as follows:

- A general theory describing the self-excitation of the most dangerous parasitic modes near cutoff in forward-wave amplifiers has been developed, first, for the case of device operation in strong focusing magnetic fields where the electrons exhibit a 1D motion and then generalized for the case of device operation in light-weight magnets providing weaker focusing and, hence allowing for electron 3D motion.
- A new type of metamaterials attractive for short wavelength high-power millimeter-wave devices has been studied: circuits loaded with periodic dielectrics and planar structures with wire sheaths deposited on dielectric layers.
- The role of metallic dust, i.e., small-size metallic micro-particles which can be melted in strong RF magnetic and electric fields of long enough pulse duration or in high rep-rate regimes, has been analyzed. Results of these studies allow researchers to evaluate conditions and operating parameters of HPM sources where the melting of such metallic micro-particles can affect reliable operation of the devices.

Our results have been described in the list of references below:

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